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Edward Reid Flynt

AN ELECTRONIC ANALOG CORRELATOR

12T

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ABSTRACT

An electronic analog computer was designed and constructed, to compute autocorrelation and crosscorrelation functions. It is capable of recording from one to four input signals simultaneously on magnetic tape, and of computing the autocorrelation function of any one of the signals or the crosscorrelation function of any pair of the signals as the tape is played back. Input signals are fluctuating voltages with amplitudes in the range from zero to one hundred volts, and with frequency components between zero and one thousand cycles per second. The variable time delay required in computing correlation functions is provided by means of a loop of the tape of adjustable length between two magnetic pickup heads. Time delays from zero to one second are available, with minimum increments of 83 microseconds. Multiplication is accomplished by means of a time-division multiplier, and the products are summed up in a Miller integrator. The computed correlation curves are displayed on a recording voltmeter. Results of tests of the individual units of the correlator are shown, together with computed correlation curves of several simple input signals. Overall error in computation is less than 5 per cent of the peak value of the correlation curve. Schematic diagrams of the major unit subassemblies are included in the Appendix.

CHAPTER I

INTRODUCTION

Methods of analysis based on the principles of mathematical statistics have played an increasingly important role in the field of engineering in recent years. Among the statistical functions that find frequent engineering application in the analysis of time series are the autocorrelation function,

$$\phi(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} f(t)\, f(t+\tau)\,dt,$$

and the crosscorrelation function,

$$\Psi(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} f(t)\, g(t+\tau)\,dt.$$

Since the data to be analyzed usually consist of the functions f(t) and g(t) defined over some finite time interval, approximations to the above correlation functions are ordinarily obtained by performing the indicated integrations over a suitably chosen finite interval in which the values of f(t) and g(t) are known. In some instances, although the functions may be continuous, it is convenient to find the values of f(t) and g(t) by sampling at a discrete set of points. In such discrete cases, the approximation to the autocorrelation function may be defined as

$$\phi(\tau) = \frac{1}{n} \sum_{i=1}^{n} f(t_i)\, f(t_i + \tau),$$

and the approximation to the crosscorrelation function may be defined as

$$\psi(\tau) = \frac{1}{n} \sum_{i=1}^{n} f(t_i)\, g(t_i + \tau).$$

In order to obtain a reasonably accurate approximation to the correlation function, a large number of samples of the functions f(t) and g(t) must be utilized, with the result that a forbidding volume of arithmetic computation is required. When it is necessary to compute a large number of correlation functions, it becomes expedient to make use of a specialized computing machine which will sample the data at suitable intervals and perform the required operations of time delay, multiplication, and summation, all at a high rate of speed.

A number of such correlation computers, or correlators, have been constructed. In one general type (1), the input functions are sampled periodically, and each sample is stored only for the time delay τ. After each pair of samples has been multiplied, the product is stored in an integrator, and the individual samples are discarded. In another type of correlator (2), the entire functions are permanently recorded in two signal channels; then the signal in one channel is delayed by the time τ with respect to the other channel, the outputs of the two channels are multiplied, and the products are summed up in an integrator.

A machine universally adaptable to all possible correlation requirements would be extremely bulky and expensive. Various applications require a wide range of choices of operating characteristics, such as amplitude and frequency limits of the input function, time delay, sampling rate, integration time, and precision. Techniques ideally suited to one type of input function may be unsatisfactory for another. Therefore, it is common practice to design a correlator for an individual application, choosing design parameters and computational techniques suitable for the requirements of the individual application.

An electronic correlator for functions containing relatively low frequency components has been designed and constructed at the Georgia Institute of Technology. The following pages contain a description of the equipment and its operation. Chapter II gives a discussion of the choice of parameters and operational techniques, and the physical division of the machine into functional subassemblies. Chapters III through VII provide more detailed descriptions of the individual subassemblies. Chapter VIII contains a discussion of test results, including sample correlation curves computed from known simple functions, and an evaluation of errors. Schematic diagrams of the major units are included in the Appendix.

CHAPTER II

GENERAL DESCRIPTION OF THE CORRELATOR

Basic performance requirements of the correlator and overall design parameters were chosen before the detailed circuit design was undertaken. Then specific operational techniques were selected for recording and reproduction of data, introduction of time delay, multiplication, integration, recording of computed results, and programming of the various operations in their proper sequence. As individual circuits were designed, they were divided into functional subassemblies for convenience in construction, operation, and maintenance. Each subassembly unit was constructed on a ninteen-inch panel for mounting in a standard relay rack. A photograph of the complete correlator, less power supplies and recording meter, is shown in Fig. 1.

The correlator was designed to meet the following performance requirements:

1. Frequency components of input signals in the range from zero to one thousand cycles per second.
2. Fluctuating input signal voltages from zero to one hundred volts.
3. Simultaneous recording of four input signals.
4. Computation of the autocorrelation function of any one of the signals, and the crosscorrelation function of any two of the signals.
5. Time delay, τ , variable from zero to one second, with minimum

Figure 1. The Correlator.

increments of approximately one hundred microseconds.

6. Maximum integration time of one minute.

7. Computational error less than 5 per cent of the maximum value of the correlation curve.

The specified accuracy requirement was such that either analog or digital techniques could be chosen. Since it appeared that an analog system meeting these requirements could be made somewhat less bulky and with fewer component parts than a digital system, analog methods were selected.

Magnetic tape was chosen as the signal recording medium. This provides a straightforward means of making a permanent record from incoming electrical signals, and of direct rereading by electrical means to reproduce the original data. It has the further advantage that recordings can be erased and the tape used again repeatedly. The tape transport unit, used in both the recording and computing operations, is described in Chapter III.

A modulation system was required to adapt the characteristics of magnetic recording to the desired signal frequency range of zero to one thousand cycles per second. Frequency modulation was chosen in preference to amplitude modulation, since frequency modulation is less sensitive to variations in uniformity of the magnetic tape. A relatively wide frequency deviation was desired, in order to minimize the effect of small fluctuations in tape speed. The lower limit of the frequency excursion is fixed by the necessity for sampling the signal voltage several times per cycle, and by the necessity for separating frequency-modulation components from signal components by filtering after the demodulation process. The upper limit of the frequency excursion is fixed by the limit of response of the magnetic tape system, which in turn is proportional to tape velocity. On the basis of these considerations, a frequency-modulation system swinging from five to fifteen kilocycles per second was adopted, together with a magnetic tape velocity of 30 inches per second. The modulation and demodulation system used is similar to that described by Green (3). Detailed descriptions of the modulator and demodulator units are contained in Chapters IV and V, respectively.

Magnetic tape recording provides a direct solution to the problem of interposing a variable time delay, τ , between the two signals applied to the multiplier. Two recording heads for each signal are provided for separate parallel tracks on the tape, with a short loop of tape between the two heads. By using these same heads for playback, the time delay between the two output signals may be varied by changing the length of the tape loop between the two heads. An idler wheel positioned by a motor driven screw controls the length of this delay loop.

In order to record four separate signals simultaneously, with two tracks on the tape for each signal, eight parallel tracks are required. A ninth track is provided for voice recording, and a tenth track for recording a constant-frequency signal for test purposes. Plastic-based magnetic tape three quarters of an inch wide is used.

One widely accepted method of analog multiplication (4) is accomplished by creating a series of rectangular pulses such that the amplitude of each pulse is proportional to the sampled value of one signal, and the width of each pulse is proportional to the sampled value of the other signal. The area of each rectangular pulse is then proportional to the product of the two samples. By summing the series of pulses thus produced, the integral of the product of two varying functions may be obtained. This basic principle of multiplication was adopted for the correlator, with modifications to make use of wave forms already present in the demodulator. The multiplier consists essentially of a gate circuit in which the completely demodulated signal in one channel is gated by a series of frequency-modulated pulses of constant width from the second channel. Multiplication can then be considered to be the result of a series of pulses whose amplitude is proportional to one signal and whose duty cycle is proportional to the other signal.

The function of the integrator cannot be divorced completely from the operation of the multiplier. Since the product term is proportional to the area of pulses, the multiplication process is not completed until the pulses have been integrated. An integrator was constructed to use the familiar Miller feedback principle. The multiplier-integrator unit is described in Chapter VI.

An output device was required, to display the completed computations. By applying the output voltage of the integrator to a recording voltmeter, a series of lines is drawn on the meter chart, the length of each line representing one point on the correlation curve. The integrator is discharged after each point is computed, thereby returning the meter stylus to its zero position. Since the meter chart advances at a uniform rate, and τ is increased at equal time intervals, the end points of the lines on the chart form a direct plot of the correlation curve.

In normal operation the data are recorded on the tape as it is wound from one reel to another. Then a sample of tape is cut off and spliced into a continuous loop. During computation this loop is run continuously through the machine, and one point on the correlation curve is computed each time the complete loop passes over the pickup heads. Two metal foil tabs are attached to the loop of tape to initiate the programming operation. As one tab passes a contact brush, the integrator is reset and τ is advanced to the next value. As the second tab passes a contact brush, computation for the new value of τ is initiated. An alternate method of programming is accomplished by resetting the system at fixed time intervals rather than by the use of contact tabs on the tape. When this method is used, the tape may be run either as a continuous loop or directly from the reels. A timer consisting of a crystal oscillator and a series of frequency dividers then provides the programming impulses. The timer unit is described in Chapter VII.

CHAPTER III

TAPE TRANSPORT UNIT

The primary function of the tape transport unit is to move the magnetic tape, either from reel to reel or in an endless loop, at a uniform velocity over the record-pickup heads. The unit has the additional function of providing variable time delay by adjusting the length of tape travel between two pickup heads. A photograph of the tape transport unit is shown in Fig. 2. The unit is similar to the tape drive systems used in sound recording, except for the addition of the time delay unit and the fact that it handles tape three quarters of an inch wide.

The pay-out and take-up reels are mounted on the shafts of torque motors. During the process of recording or playback from the reels, a reduced voltage applied to both motors provides uniform tension in the tape. Rapid rewinding in either direction may be accomplished by applying full voltage to either one of the motors. When an endless loop of tape is used, these motors are not energized. A magnetic brake on the shafts of the motors stops the reels when the unit is turned off.

The tape is driven by a ground metal capstan mounted on the shaft of a flywheel, which is driven at constant speed by a hysteresis synchronous motor. The tape passes between the capstan and a rubber roller, then over one record-pickup head, over the adjustable idler of the time delay mechanism, past the second head, and again between the capstan and a second rubber roller. The rubber pinch rollers are engaged by a solenoid during

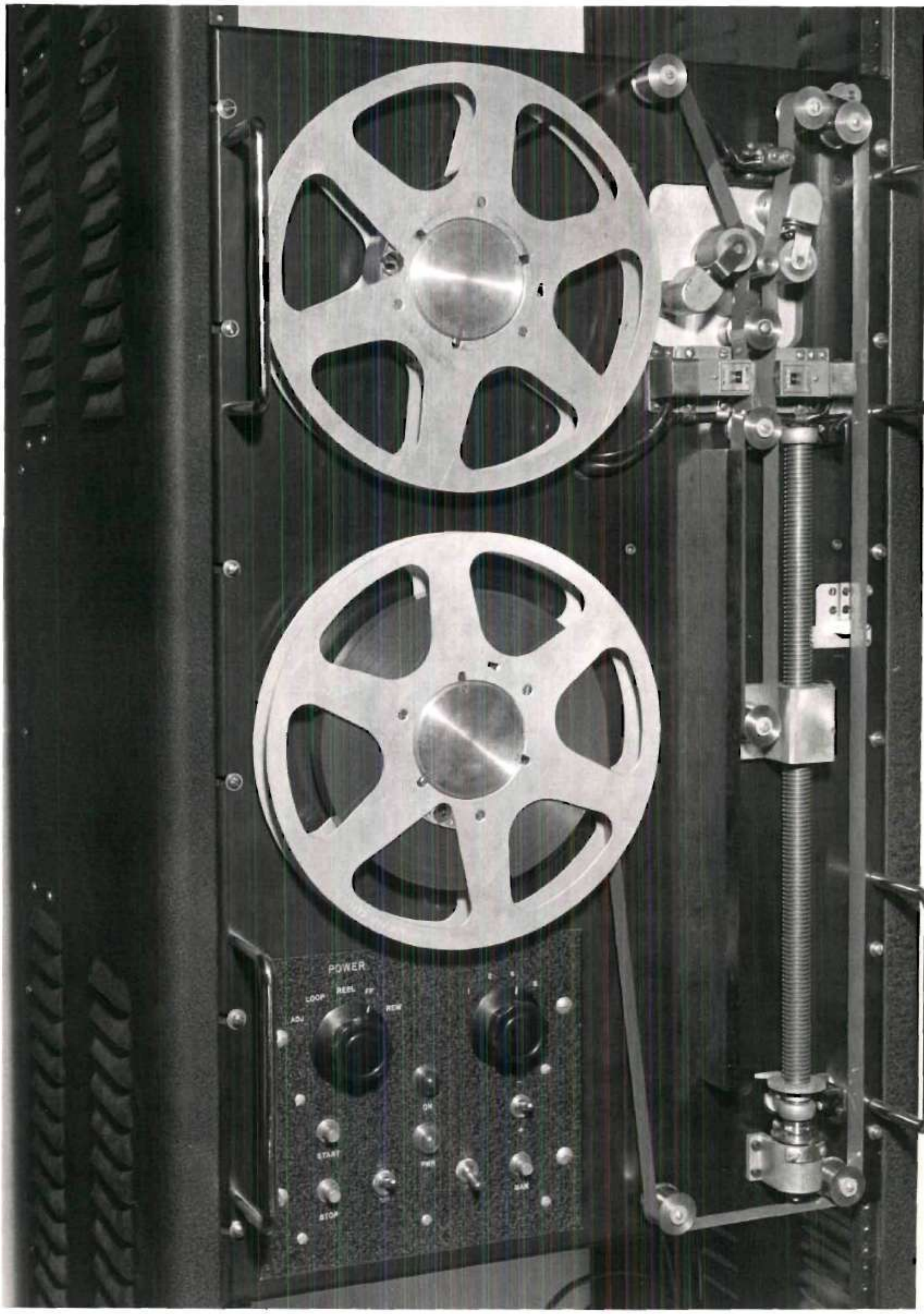


Figure 2. Tape Transport Unit.

operation, and released when the unit is turned off.

A permanent magnet is used for erasing the tape during the recording operation. It is mounted before the heads in such a way that it can be folded back away from the tape during playback. A contact brush assembly makes contact with two metal foil tabs attached to the tape, providing programming impulses to the multiplier-integrator unit each time the tape loop passes through the machine. An interlock switch held closed by the tape tension stops the machine in the event of tape breakage.

The time delay mechanism consists of an idler roller in the tape path, positioned by a motor-driven screw. When a time-delay impulse is received from the multiplier-integrator, the motor advances the idler by a predetermined distance, increasing the length of tape between the two head assemblies, and thereby increasing the time delay between the two output signals. A rotary switch selects the distance traveled by the idler at each impulse. The switch provides time-delay increments of 83 microseconds, 167 microseconds, 333 microseconds, or 667 microseconds. The total travel of the idler provides time delays from zero to one second.

In order to minimize fluctuations in tape velocity, all moving parts in the tape path were machined to close tolerances, and the flywheel was dynamically balanced. Sleeve bearings were used on all rotating parts to reduce bearing rumble.

CHAPTER IV

MODULATOR UNIT

The modulator unit accepts as input signals the fluctuating voltages for which correlation functions are to be computed, and delivers frequency-modulated signals, deviating between five and fifteen kilocycles per second, to the magnetic recording heads. In order to record four input signals simultaneously, the correlator has two modulator units, each of which has two identical signal channels. Each signal channel in turn has outputs to two recording heads, in order to record each signal on two parallel tracks on the magnetic tape. The operation of one of the four identical signal channels will be described. A photograph of one modulator unit is shown in Fig. 3.

The input signal first passes through a direct-coupled amplifier with controls for gain and d.c. level, so that a wide range of input signals can be adjusted to make use of the total excursion of the frequency-modulator. The amplifier is a modification of a circuit described by Goldberg (5). The balanced nature of this circuit provides a considerable degree of compensation for changes in supply voltages and characteristics of components. A large amount of negative feedback results in linearity and in stability gain.

The input amplifier is followed by a level indicating device. Since both amplitude and d.c. level of the signal must be adjusted, a dual indicator is required. Two indicator tubes of the tuning-eye type are

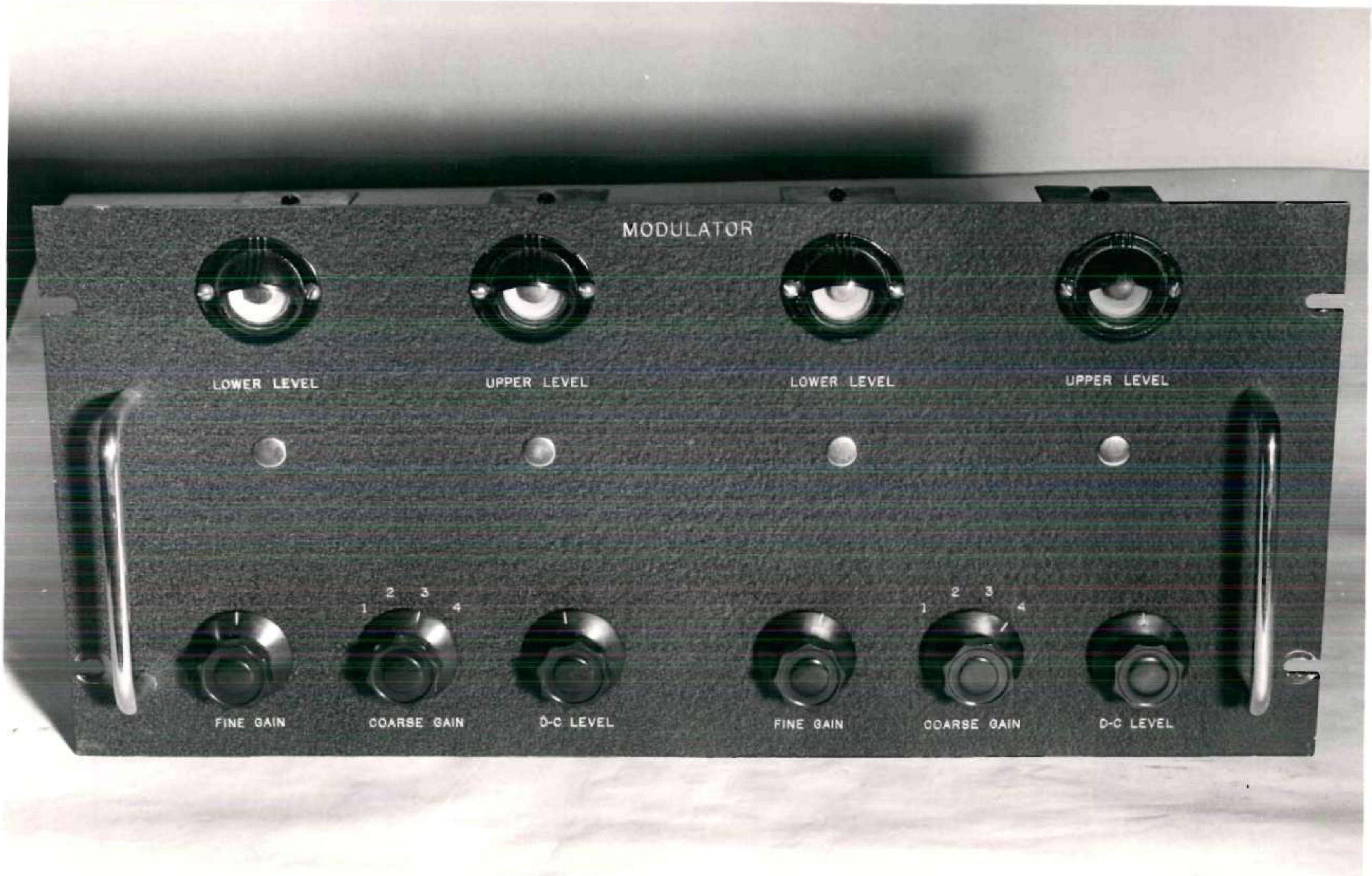


Figure 3. Modulator Unit.

used. One indicator is so adjusted that the eye is completely closed when the output voltage of the signal amplifier is such as to produce a frequency of five kilocycles per second in the frequency-modulator. The other indicator is so adjusted that the eye is completely closed when the voltage is such as to produce fifteen kilocycles per second in the frequency-modulator. Both eyes are completely open when the frequency is within the range of about six to fourteen kilocycles. In operation, the amplifier gain and level controls are set so that occasional signal peaks cause each indicator eye to close, but never to go beyond the point of complete closure.

The level indicator is followed by the frequency-modulator stage. This stage is simply an astable multivibrator, with the signal voltage applied to the grid returns of the two triode sections. The performance of such a circuit is described by Bertram (6). Component values were so chosen that the frequency varies linearly with input voltage over a range from five to fifteen kilocycles.

A conventional amplifier following the frequency-modulator provides sufficient power to drive two magnetic recording heads in parallel.

CHAPTER V

DEMODULATOR UNIT

The demodulator unit receives frequency-modulated signals from the magnetic heads during the playback operation, and demodulates them to reproduce the original signals, $f(t)$ and $g(t)$. A photograph of the demodulator unit is shown in Fig. 4.

A selector switch on the demodulator unit provides the choice between recording and playback operations. In the recording position, the magnetic heads on the tape transport unit are connected to the output of the modulators, and plate supply voltages are connected to the modulators and disconnected from the demodulator and multiplier-integrator. In the playback position, the magnetic heads are connected to the input of the demodulator, and plate supply voltages are removed from the modulators and connected to the demodulator and multiplier-integrator. Two lights on the front panel indicate the position of the record-playback switch.

Two complete frequency-demodulators are included in the demodulator unit. A selector switch, labeled F, connects one demodulator channel to any one of the four pickup heads in one head assembly. Another switch, labeled G, connects the other demodulator channel to any one of the four pickup heads in the other head assembly. By setting both selectors to the same numbered channel, the autocorrelation function of any one of the four recorded signals may be computed. By setting one selector to one channel and one to another, the crosscorrelation of any pair of the four recorded

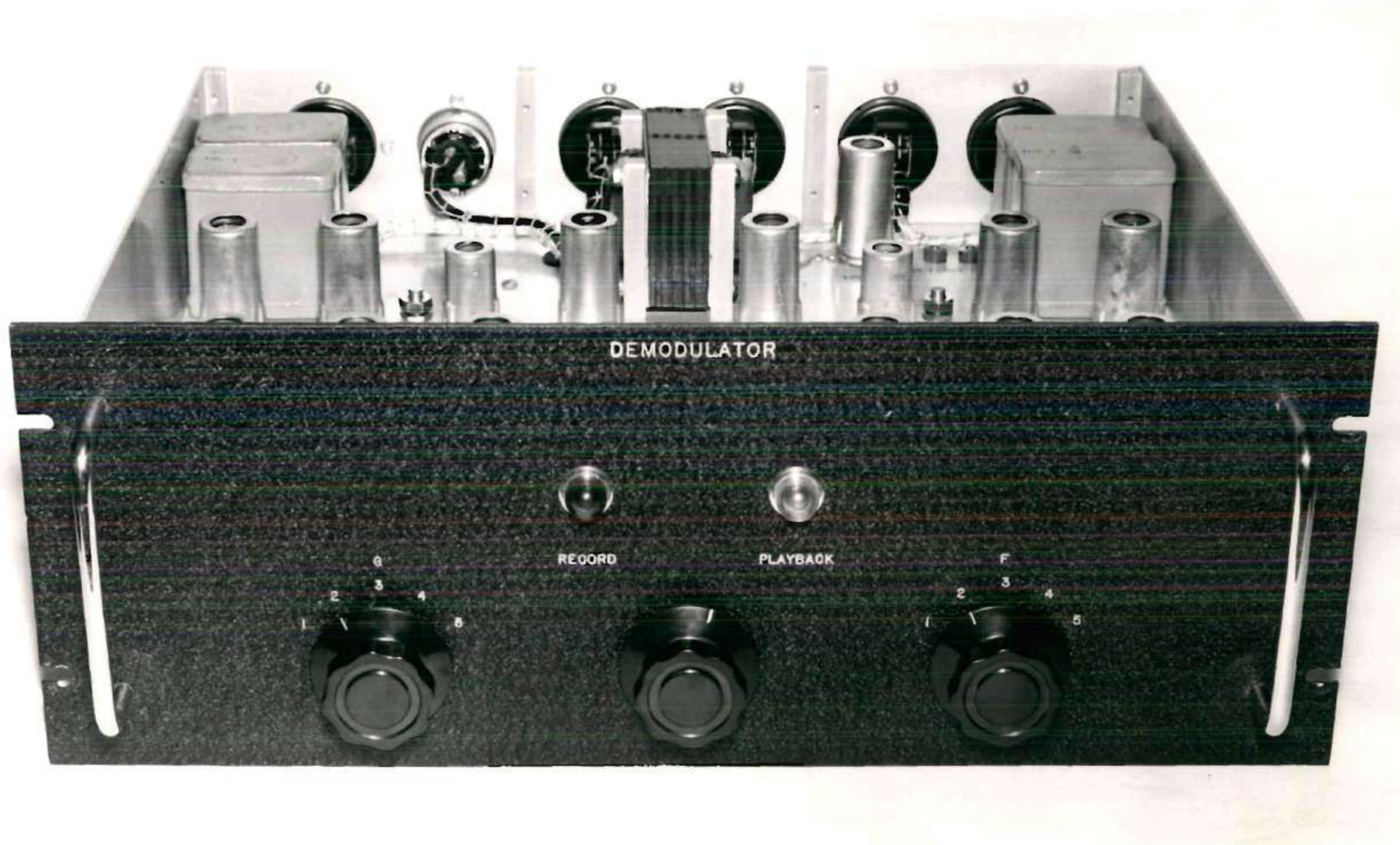


Figure 4. Demodulator Unit.

signals may be computed.

Each demodulator channel consists of a conventional R-C coupled preamplifier, a series of cathode-coupled clippers, a frequency-demodulator of the cycle-counting type, and a low-pass filter.

The preamplifier receives a frequency-modulated signal with amplitude of the order of a few millivolts from the pickup head, and amplifies it sufficiently to drive the demodulator. The amplifier was designed to respond to the frequency-modulated signal in the range of five to fifteen kilocycles, but to have very low response at power line frequencies, in order to minimize hum pickup. The clippers shape the waveform and remove any amplitude modulation that is present.

The frequency-demodulator stage consists of a monostable multivibrator and a low-pass filter. The multivibrator is triggered by the output of the clipper, producing one pulse of constant area for each cycle of the frequency-modulated signal. The mean value of this pulse train therefore varies directly with frequency, and constitutes the demodulated signal. The pulse frequency components are removed from the demodulated output by means of a low-pass filter, consisting of one T-section and one L-section. The filter has essentially flat response from d.c. to one thousand cycles, and attenuation of forty db or more at all frequencies above five kilocycles. The demodulated signal output varies linearly from about twenty to forty volts as the frequency-modulated input varies from five to fifteen kilocycles.

The outputs of the low-pass filters of both demodulator channels are brought out to cable connectors. In addition, the train of constant-width frequency-modulated pulses from the monostable multivibrator of one channel is brought out to a connector, for use in the multiplier.

CHAPTER VI

MULTIPLIER-INTEGRATOR UNIT

The multiplier-integrator unit contains the multiplier gate circuits, the integrator, a power amplifier for driving the output recorder, and the various balancing and calibration controls. A photograph of the multiplier-integrator is shown in Fig. 5.

The multiplier receives an input from each of the two demodulator channels. One input, referred to as the F signal, is the filtered output of one of the demodulators. This signal is a reproduction of one of the originally recorded signals, containing frequency components from zero to one thousand cycles per second. The other input, referred to as the G signal, is the train of constant-width frequency-modulated pulses from the second demodulator channel. The frequency, and consequently the duty cycle, of these pulses varies with the amplitude of the originally recorded signal in that channel. The G signal pulses are used to gate the F signal in the multiplier, resulting in a train of pulses whose amplitudes vary with the F signal and whose duty cycle varies with the G signal. The mean area of these pulses is then proportional to the mean product of the F and G signals.

The multiplier gate is similar to a circuit described by Morrill and Baum (7). It consists of a direct-coupled feedback amplifier, with an electronic switch to connect the feedback path alternately to two identical resistive circuits. The amplifier has an overall gain with feedback of -1. The

Figure 5. Multiplier - Integrator Unit.

output is taken from one of the two feedback circuits. If the input signal to the amplifier is designated as F, the output is a series of pulses with an amplitude of -F, and width and frequency the same as the gating G pulses. The circuit is capable of receiving either positive or negative F signals, and delivering negative or positive pulses. Since gating is accomplished by switching between identical feedback paths, the amplifier itself is not actually gated, and need not be capable of responding to the high-frequency gate pulses.

The mean value of the F signal is balanced out ahead of the multiplier, by means of a variable voltage divider between the input signal and a fixed negative voltage. The control for this operation is labeled F BALANCE. The mean value of the G signal takes the form of the mean duty-cycle of the G pulses. This mean value is balanced out by subtracting from the multiplier output a fraction of the F signal, this fraction being adjusted to correspond to the mean duty cycle of G. The control for this adjustment is labeled G BALANCE. A third control on the multiplier, labeled MULTIPLIER BALANCE, is provided to compensate for long-time drift in the d.c. amplifier. A fourth control, labeled GAIN, adjusts the amplitude of the F signal input to the multiplier.

The integrator circuit makes use of the familiar Miller feedback principle. It consists of a direct-coupled amplifier with high negative gain, with a condenser from output to input and a resistor in series with the input. The output voltage of such a circuit is proportional to the time integral of the input voltage. The initial voltage is established by charging the condenser to the required voltage at the beginning of each integration period, by means of a reset circuit. This circuit consists of a relay driven by a bistable multivibrator, and an adjustable voltage divider to control the reset voltage. When the relay is in the reset position, the integrator condenser is connected to the adjustable d.c. voltage divider. In the integrate position, the condenser is connected to the integrator amplifier.

The integrator can be made to reset automatically either at fixed time intervals or once each time the tape loop passes through the machine, or it can be set manually to reset or to integrate. This operation is selected by means of a four-position switch on the front panel. In the TIMER position, pulses from the timer unit reset the integrator at periodic intervals. In the TAB position, a metal foil tab on the magnetic tape causes the integrator to reset and a second tab causes it to resume integration once each time the tape loop passes through the machine. In the RESET position, the integrator is reset and remains idle, and in the INTEGRATE position, integration takes place continuously until the control is changed.

The voltage to which the integrator is reset determines the zero point on the output recorder, and is adjusted by means of a control marked ZERO. A control to compensate for long-time drift in the integrator amplifier is marked INTEGRATOR BALANCE. The value of the integrating condenser is selected by means of a control marked C. Two indicator lights show whether the circuit is integrating or reset. A CALIBRATE switch sets up calibration circuits for adjusting each of the controls in proper sequence.

The voltage across the integrating condenser is continuously recorded on a recording voltmeter, during both the integration and reset periods. A direct-coupled power amplifier provides push-pull output sufficient to drive the meter mechanism.

CHAPTER VII

AUXILIARY UNITS

In addition to the primary components already described, there are a number of auxiliary units of the correlator that should be mentioned. These include the timer unit, the output recorder, the voice unit, and the power supplies.

The timer consists of a 120-kilocycle crystal oscillator, a series of phantastron frequency dividers, and a series of bistable scale-of-two frequency dividers. Pulses are available from this chain at fifteen different repetition frequencies, ranging from 120 kilocycles per second to one cycle in 64 seconds. The lower-frequency dividers, below one cycle per second, are physically located on the voice unit, but are functionally a part of the timer. The six kilocycle output is recorded on one track of the magnetic tape for the purpose of monitoring the tape speed. The sixty cycle output may be filtered and amplified, and used to drive the synchronous motors if the machine is used in a location where constant-frequency power is not available. Any one of the low-frequency outputs may be selected for programming the machine, when it is desired to reset at fixed time intervals rather than at fixed positions on the tape. A photograph of the timer unit is shown in Fig. 6.

The output recorder is a Sanborn Model 127 T recording voltmeter. This recorder produces a chart in true rectangular coordinates by pulling the paper over a straight knife-edge under the writing stylus, eliminating

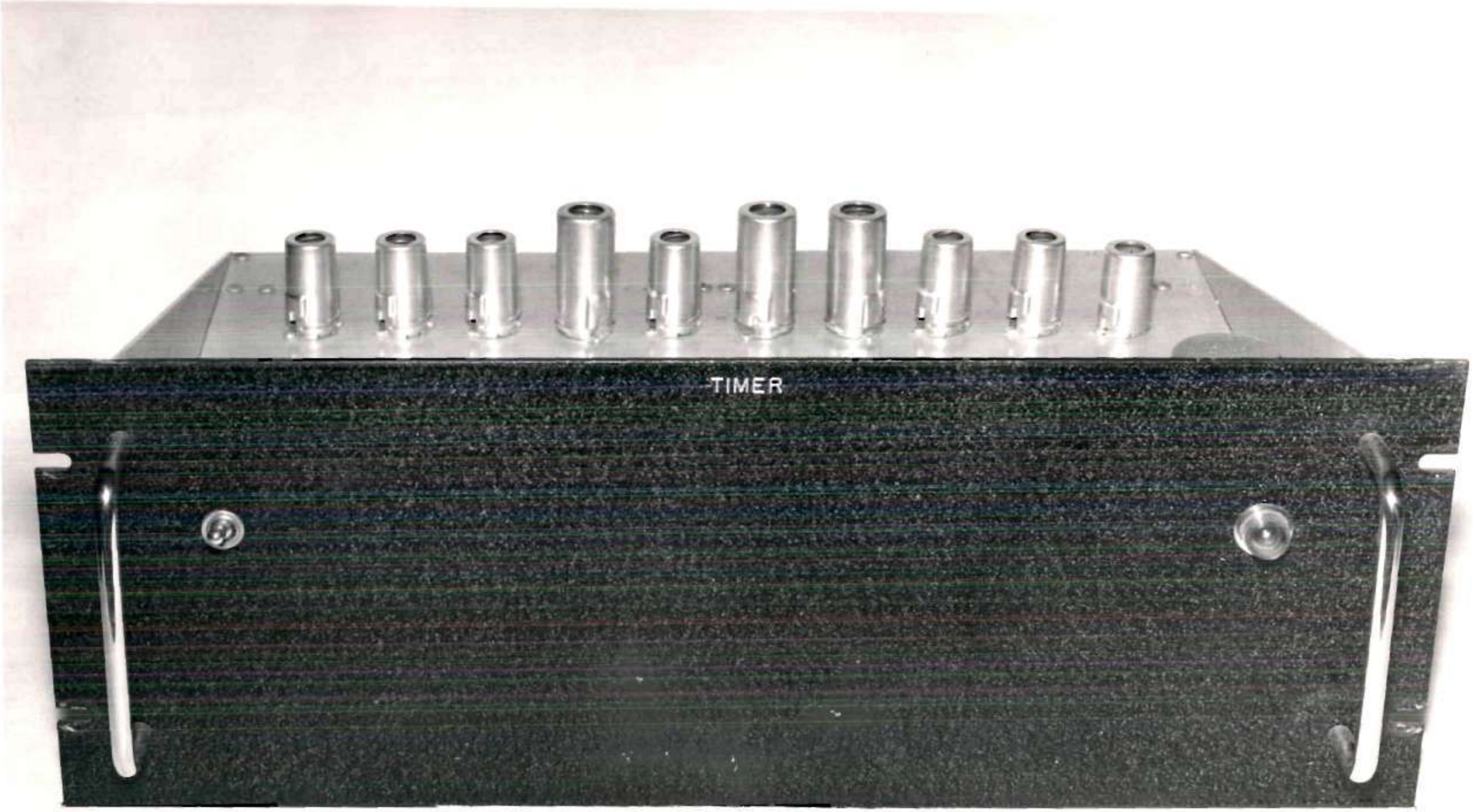


Figure 6. Timer Unit.

the usual circular writing arc. A high torque-to-weight ratio minimizes friction errors. Recording is done by means of a heated stylus on heat-sensitive paper. The paper drive motor was changed to produce a chart speed of one-tenth millimeter per second.

A voice unit permits the recording of speech on one track of the magnetic tape, and reproduction of the speech during playback. This facilitates identification of data recorded on the other tracks. The voice unit contains the recording and playback amplifier, and bias oscillator, as used in standard audio recording practice (8). Requirements of frequency range and amplitude linearity were not as severe as for the usual audio applications, since only speech intelligibility is required. As stated above, the low-frequency part of the timer is also located on this unit. A photograph of the voice unit is shown in Fig. 7.

The power supplies are standard commercially built units, supplying regulated d.c. power at 150 and 300 volts positive and 150 volts negative, with a maximum current of three hundred milliamperes at either voltage. Heater current is furnished by a separate transformer on each unit. Power for the d.c. power supplies, the heater transformers, and the drive motors is furnished by a 115-volt 60-cycle line, with a total load of approximately 16 amperes.

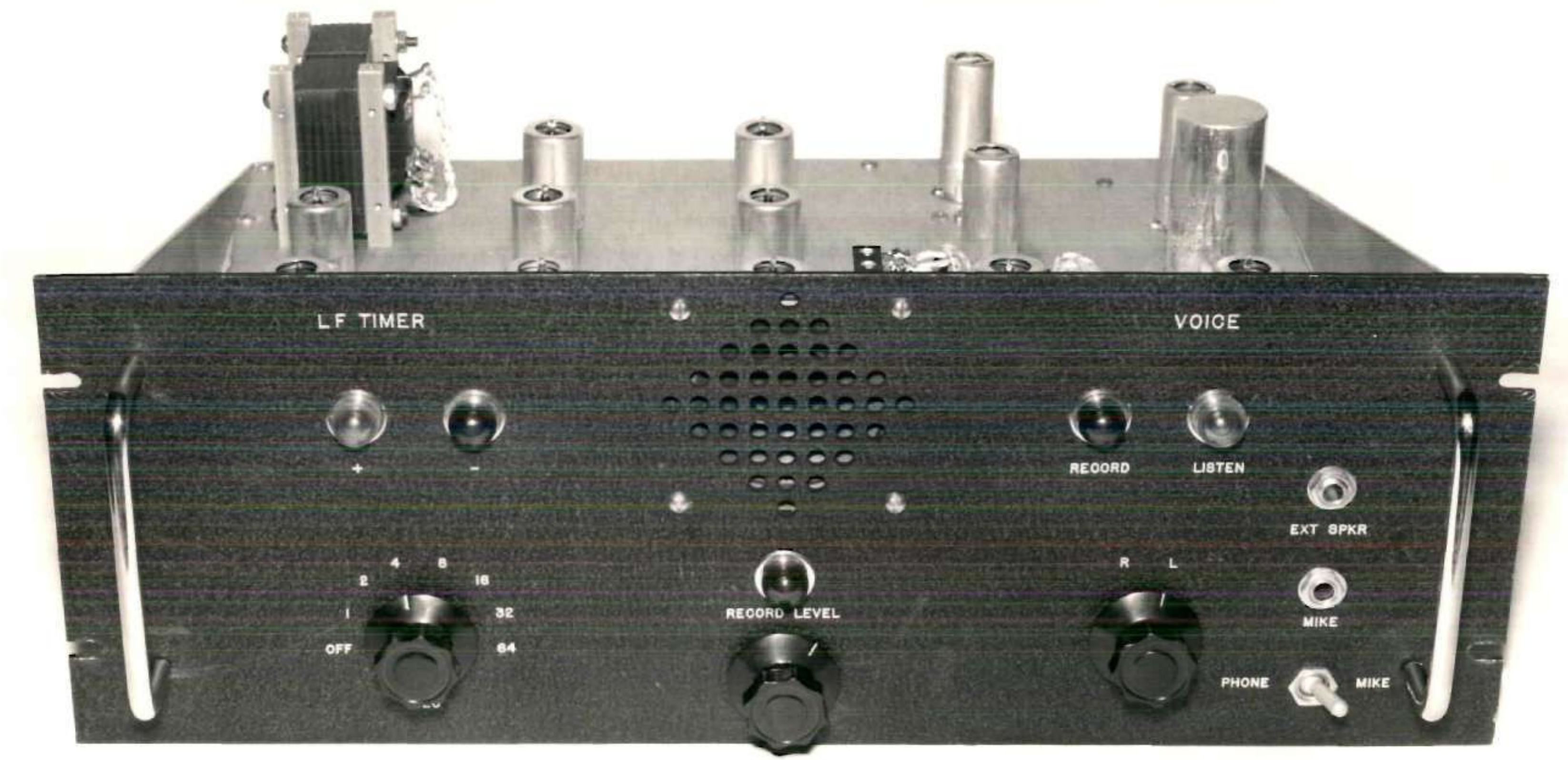


Figure 7. Voice Unit.

CHAPTER VIII

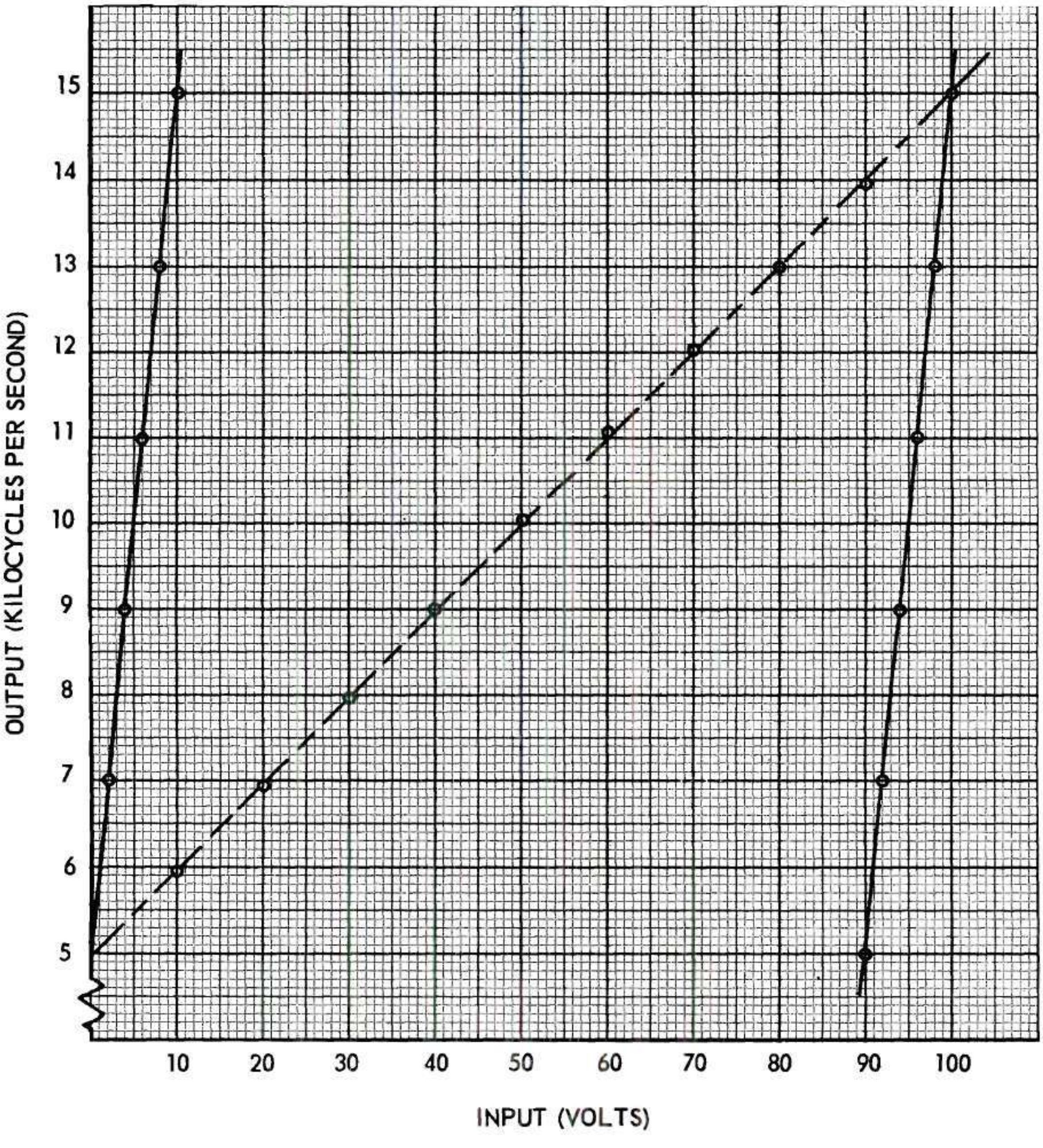
TEST RESULTS

Performance tests were made on individual units of the correlator to determine their linearity and stability. In addition, correlation functions were computed for a number of simple input signals, as a means of evaluating the overall performance of the machine.

In order to measure the amount of flutter in the tape transport unit, a constant frequency was recorded on the tape and played back through the frequency demodulator. Any fluctuation in tape velocity, in either the recording or playback operations, results in a variation in amplitude of the demodulator output. The demodulated signal was displayed on an oscilloscope, and the measured amplitude of fluctuation was found to be about forty db below the maximum signal range of the system.

Curves showing the linearity of one of the modulator units are presented in Fig. 8. The three curves represent two arbitrary settings of the gain control and three arbitrary settings of the d.c. level control on the modulator. The normal operating ranges of input signals from zero to one hundred volts and output frequencies from five to fifteen kilocycles are illustrated. Similar results were obtained from tests of the other modulators.

The linearity of one of the demodulator channels is illustrated in Fig. 9. In this test, periodic signals in the range from five to fifteen kilocycles were fed into the demodulator, and output voltage was plotted



Note: The three curves represent two arbitrary gain control settings and three arbitrary d. c. level settings.

Figure 8. Modulator Characteristic Curves.

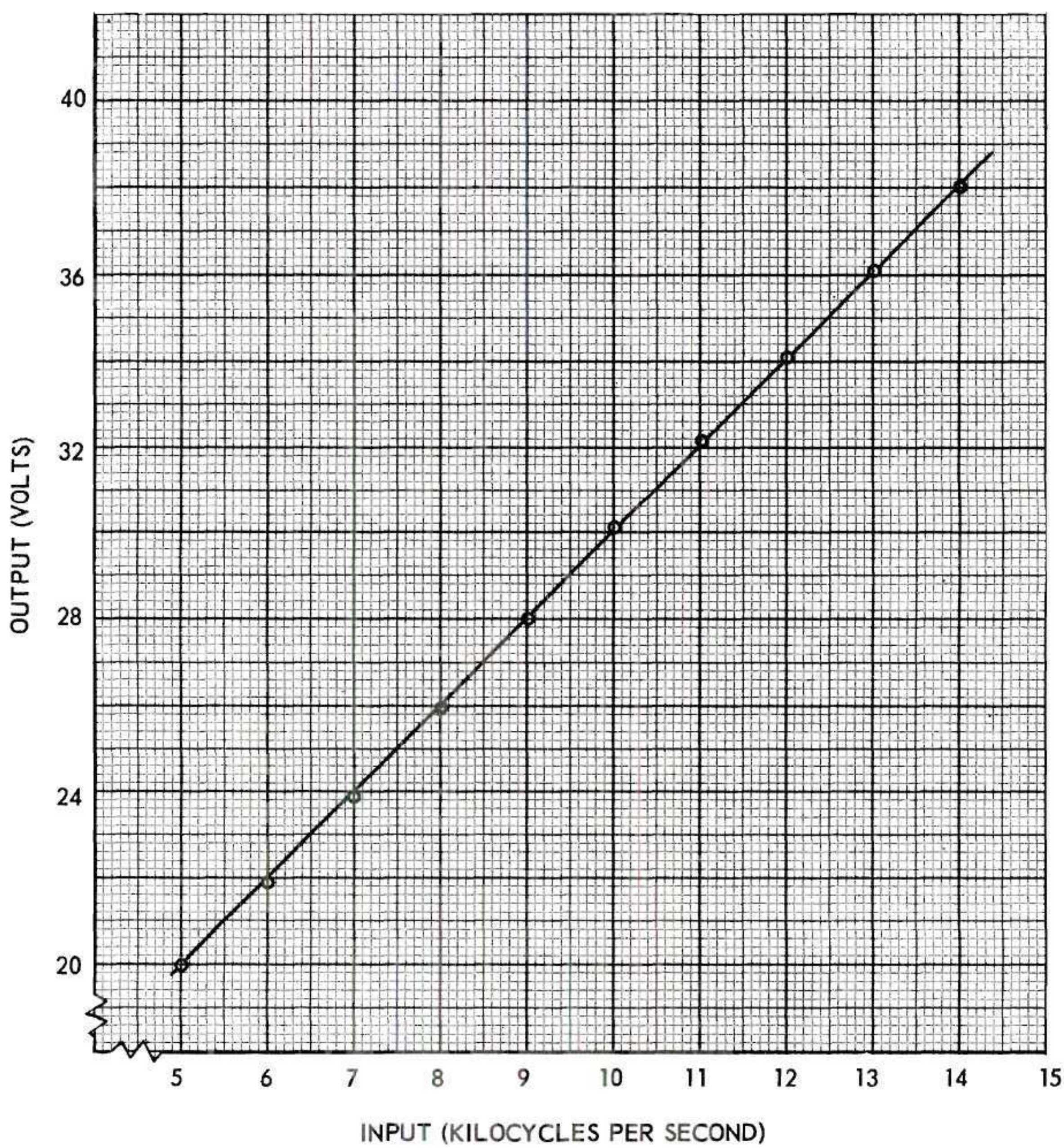


Figure 9. Demodulator Characteristic Curve.

against input frequency. A test of the other demodulator channel produced similar results.

A test of signal distortion by the modulation, recording, playback and demodulation system was made by applying sine waves of ten cycles, one hundred cycles, and one thousand cycles in sequence to the modulator and measuring the demodulated outputs with a wave analyzer. The output signals contained 3 per cent of second harmonic, 0.5 per cent of third harmonic, and negligible amounts of higher harmonic distortion.

A frequency response curve of the data recording and playback system is shown in Fig. 10. This was made by feeding into the machine a sine wave of constant amplitude and variable frequency, and by performing the operations of frequency modulation, magnetic recording and playback, and demodulation. The demodulator output amplitude is essentially independent of frequency over the desired signal frequency range of zero to one thousand cycles per second. The zero-frequency point, not shown on the curve, was obtained by applying two d.c. voltages in turn to the input.

A dynamic test of frequency response was made by recording a square wave of one hundred cycles per second. The demodulated output appeared on an oscilloscope as a square wave with only a slight overshoot on the leading edge. Measurement with a wave analyzer indicated relative amplitudes of harmonic components essentially the same as for a pure square wave. The measured values were: fundamental, 100; third harmonic, 33; fifth harmonic, 20; seventh harmonic, 14; ninth harmonic, 11; eleventh harmonic, 9; even-order-harmonics, negligible.

Linearity of the integrator is indicated by Figs. 11 and 12. Fig. 11 shows integrator output as a function of time, with a constant input voltage,

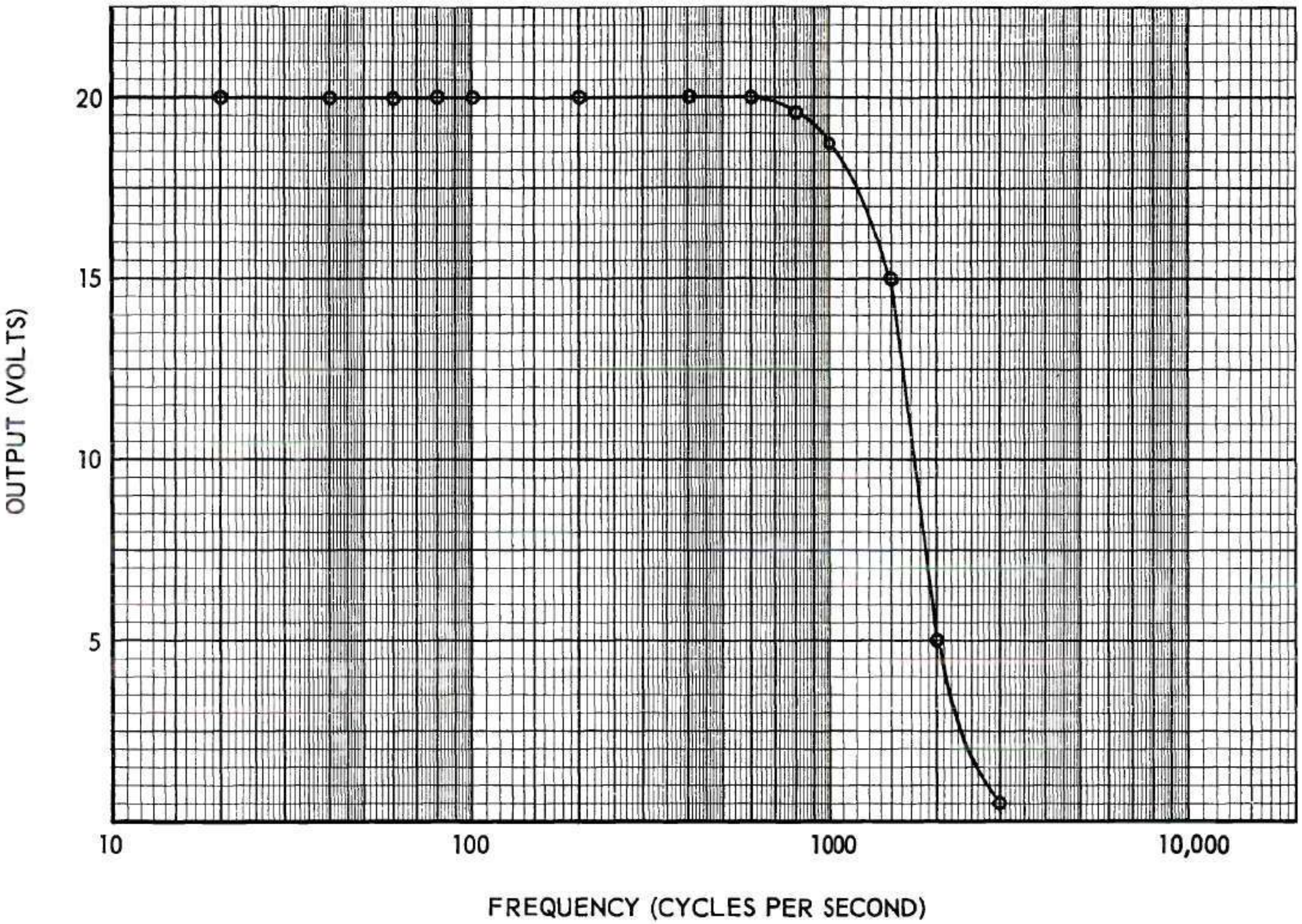


Figure 10. Frequency Response Curve of Modulator, Magnetic Tape, and Demodulator.

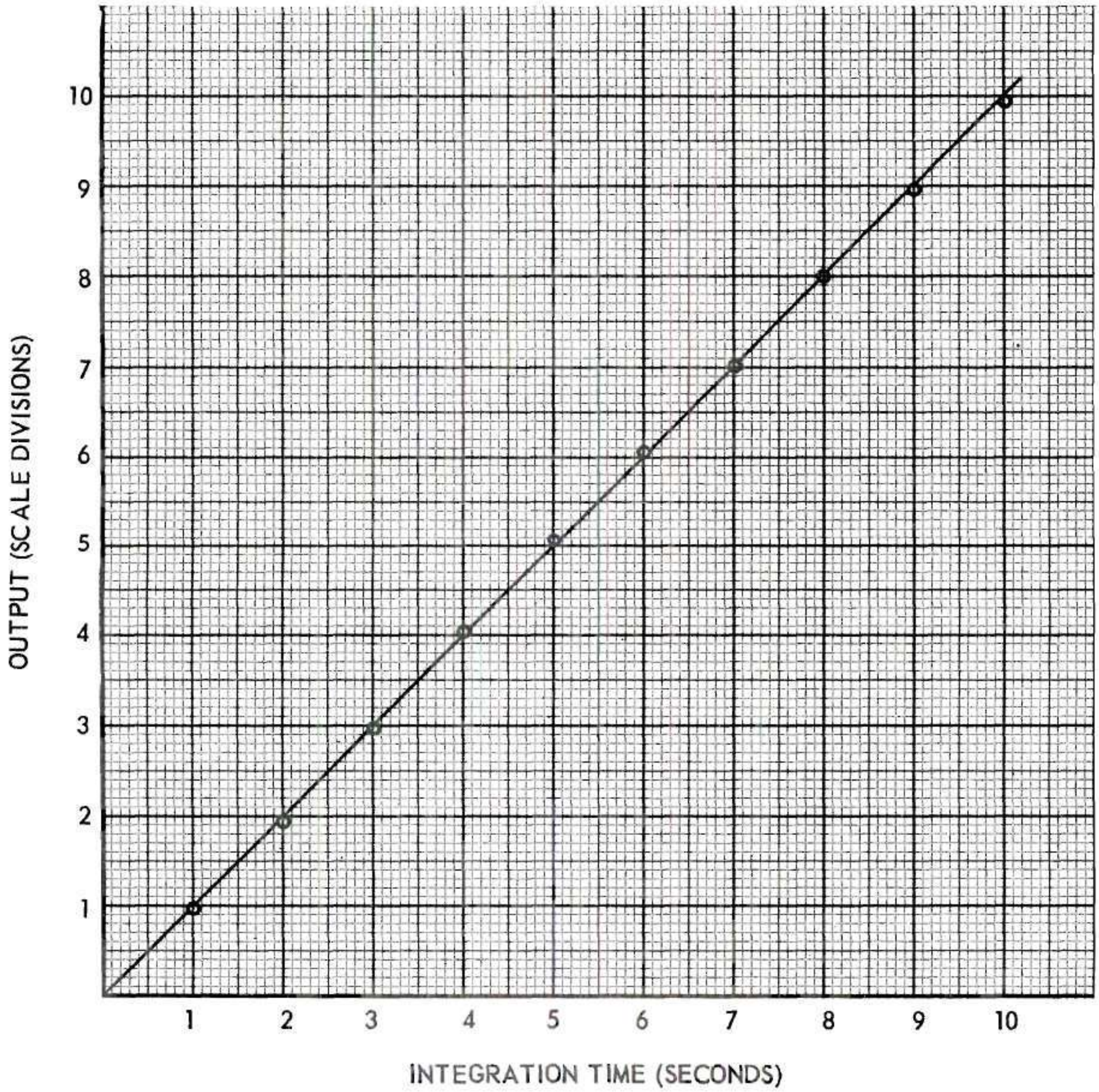


Figure 11. Integrator Characteristic Curve, with Constant Input Voltage.

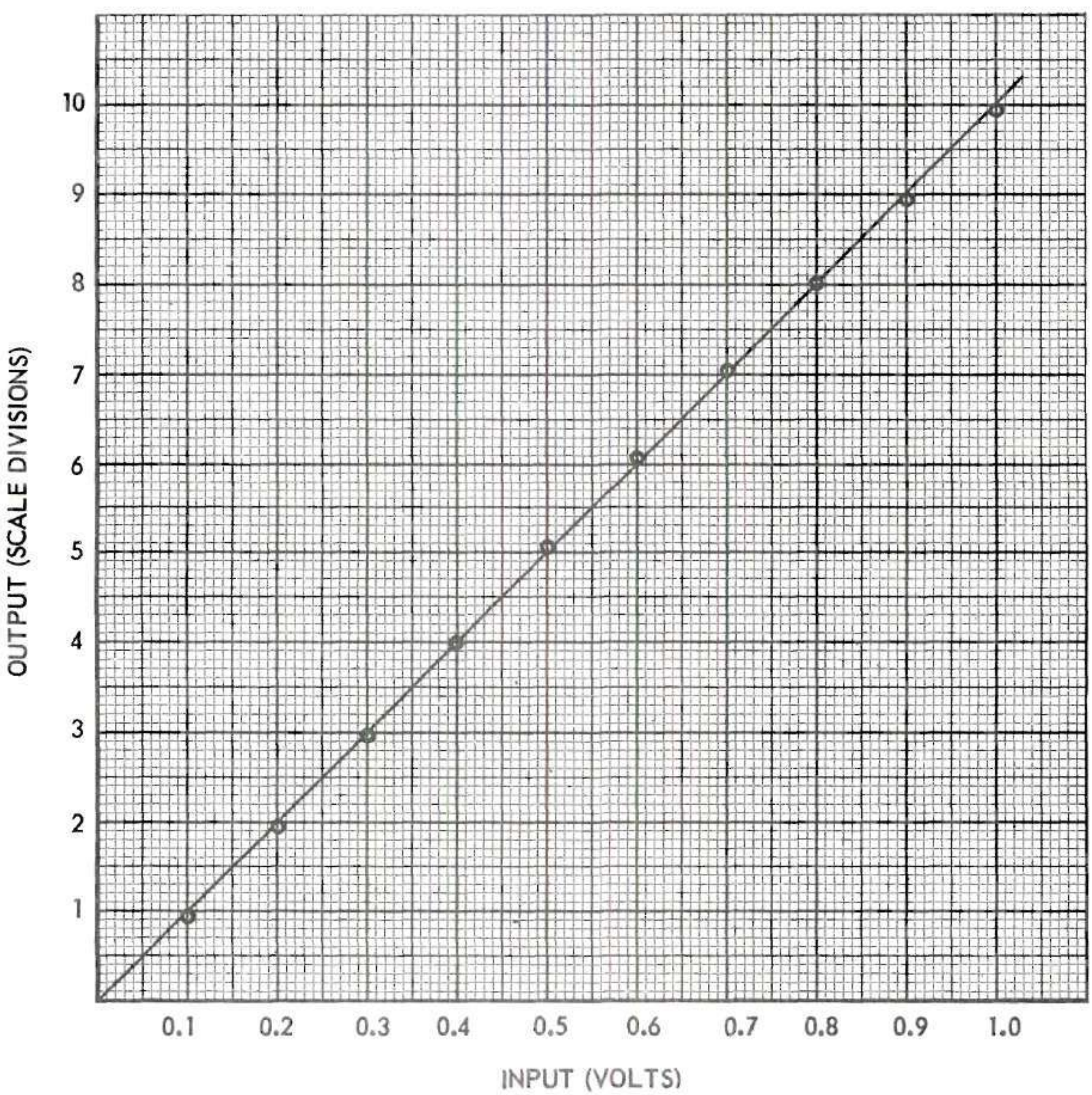


Figure 12. Integrator Characteristic Curve, with Constant Integration Time.

while Fig. 12 shows integrator output as a function of input voltage, with constant integration time. These tests were made with an arbitrary value of the adjustable integration time constant. The output voltages were read by means of the correlator's output recorder, so that the curves also include a test of the linearity of the recorder and its driving amplifier.

Two tests of the multiplier linearity are illustrated in Figs. 13 and 14. Fig. 13 is a plot of the multiplier-integrator output with a constant voltage in the multiplier F-channel and variable frequency in the G-channel. Fig. 14 is a plot of the multiplier-integrator output with a constant frequency in the multiplier G-channel and variable voltage in the F-channel. Both were made with an arbitrary fixed integration time.

The computed autocorrelation function for a sine wave of fifty cycles per second is shown in Fig. 15. The shape of this computed curve compares favorably with the cosine curve that is to be expected from theoretical considerations.

The computed autocorrelation function of a square wave of one hundred cycles per second is shown in Fig. 16. This curve compares favorably with the series of isosceles triangles expected from theoretical considerations.

A typical autocorrelation function of a filtered low-frequency random-noise signal is shown in Fig. 17. The autocorrelation function of a signal consisting of a sine wave twenty db below the random noise level is shown in Fig. 18. In Fig. 19 is shown the crosscorrelation function of a sine wave signal and a signal consisting of a sine wave of the same frequency, forty db below the noise level. These curves illustrate one of the applications (9) of correlation techniques in detecting the presence of

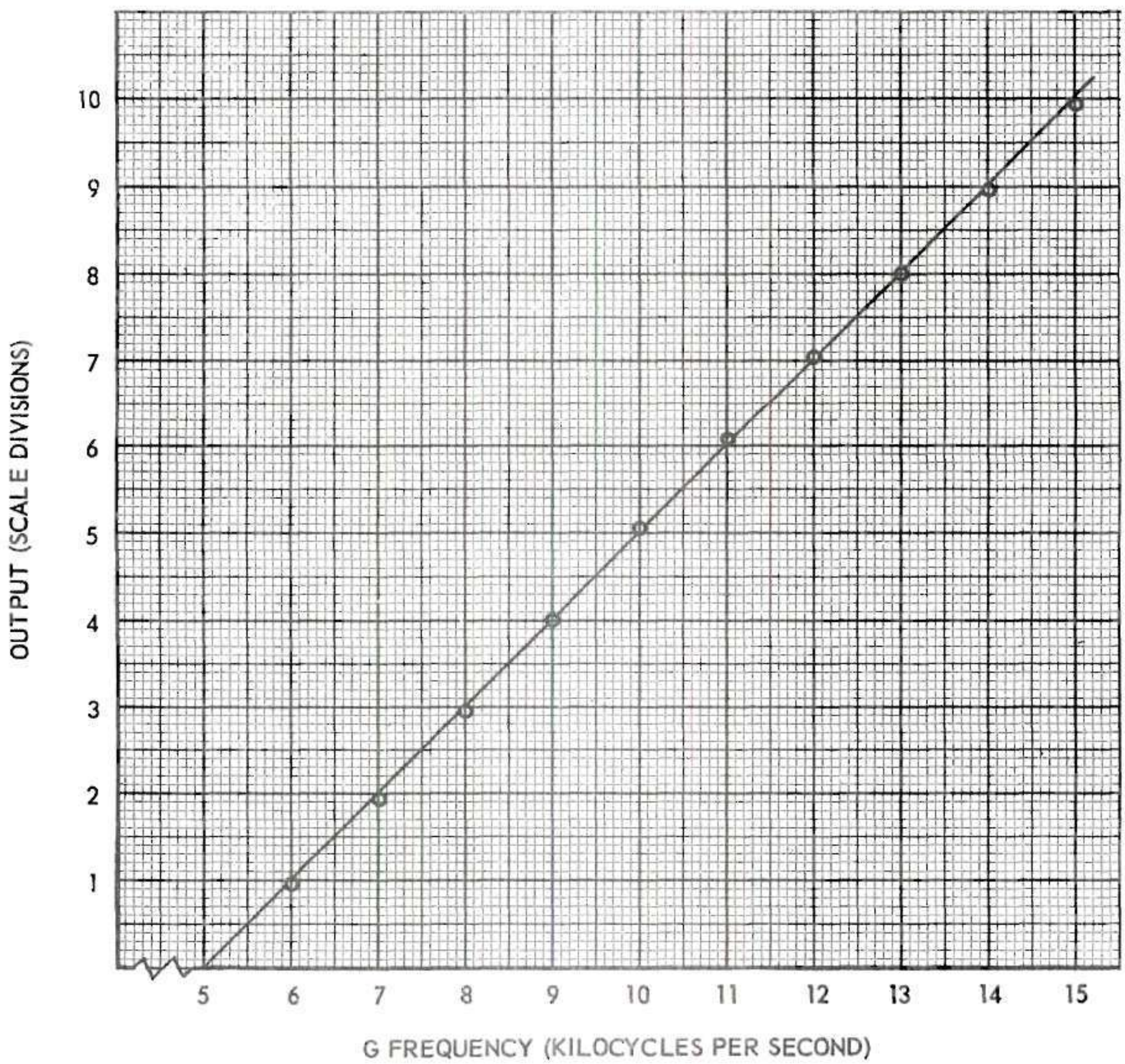


Figure 13. Multiplier - Integrator Output with Constant F - Signal and Variable G - Signal.

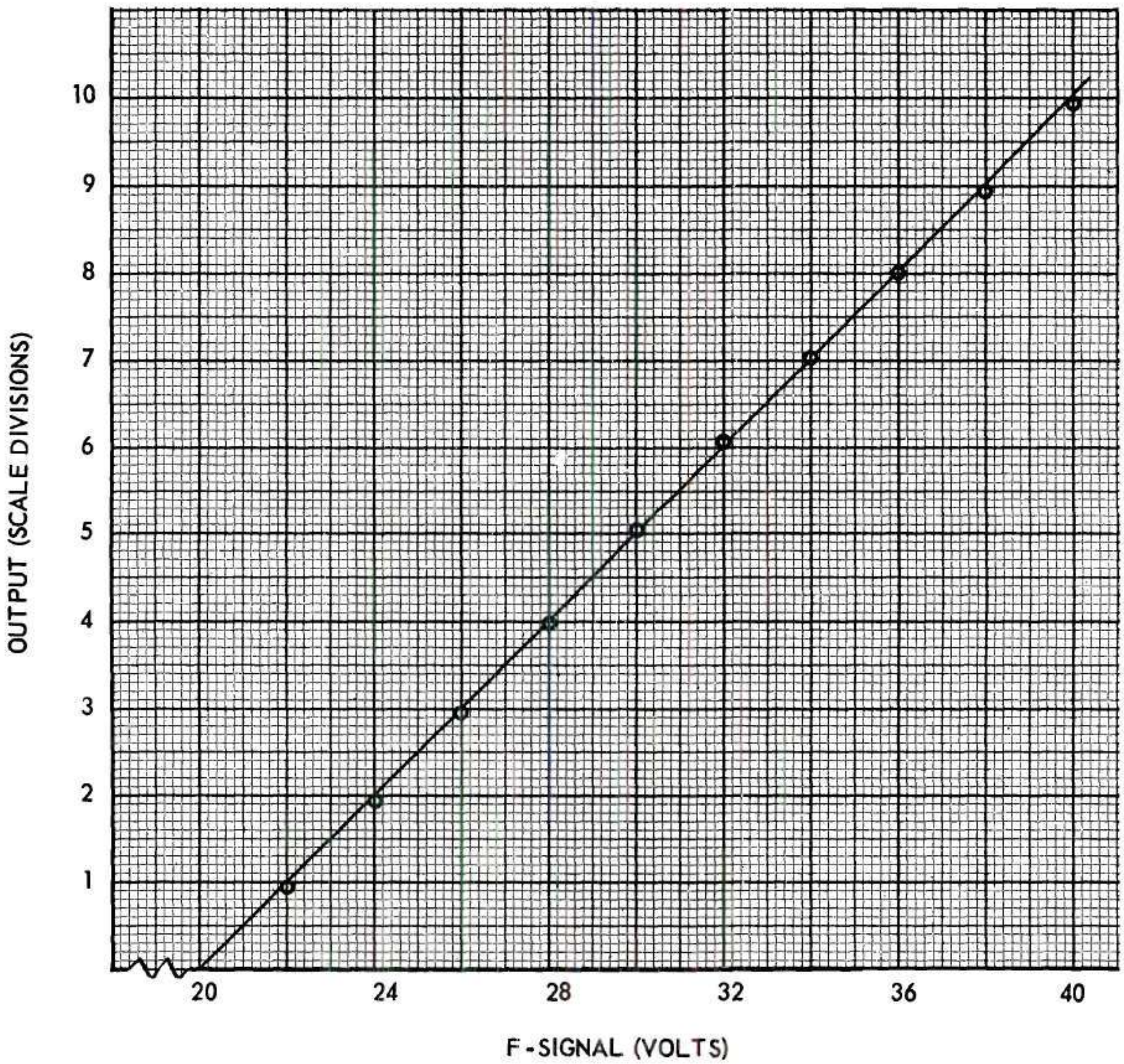


Figure 14. Multiplier - Integrator Output with Constant G - Signal and Variable F - Signal.

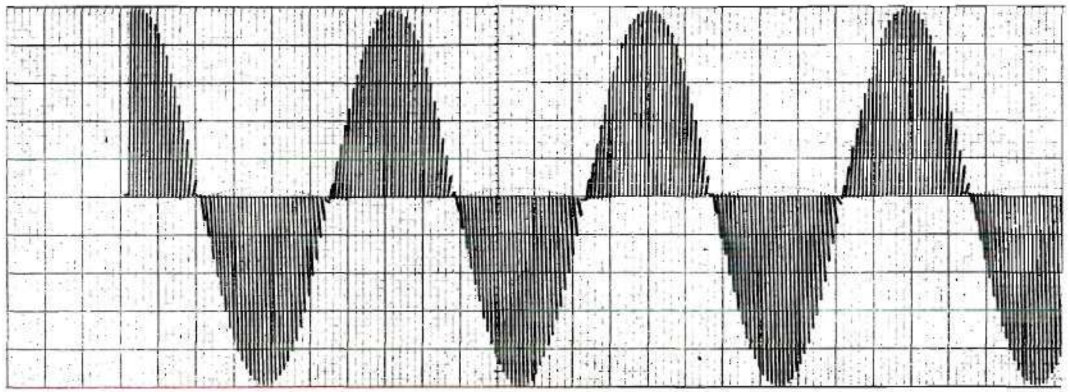


Figure 15. Computed Autocorrelation Function of a Sine Wave.

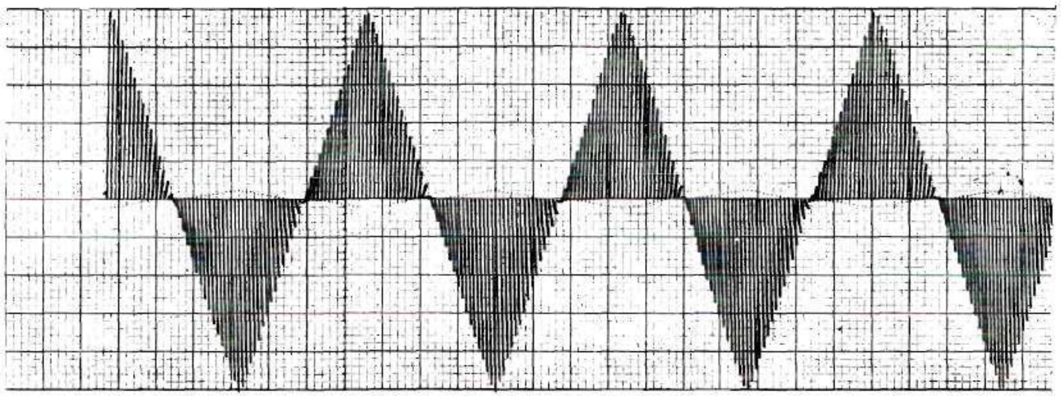


Figure 16. Computed Autocorrelation Function of a Square Wave.

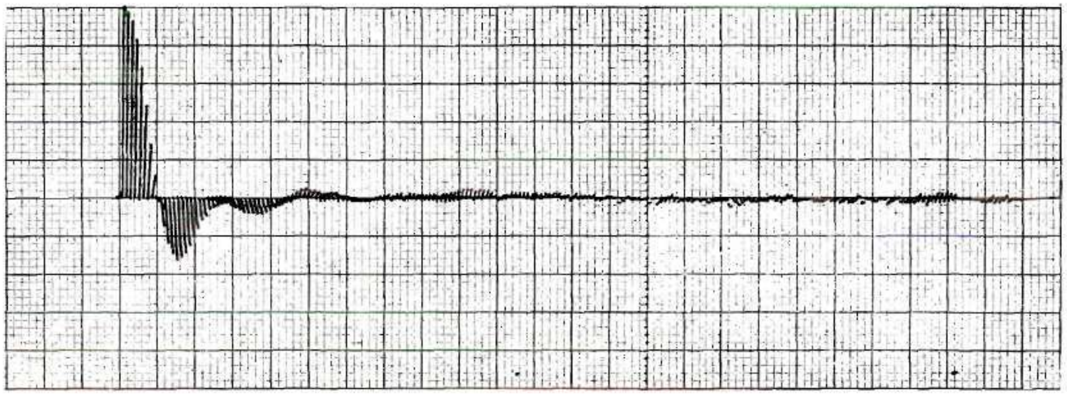


Figure 17. Computed Autocorrelation Function of Filtered Random Noise.

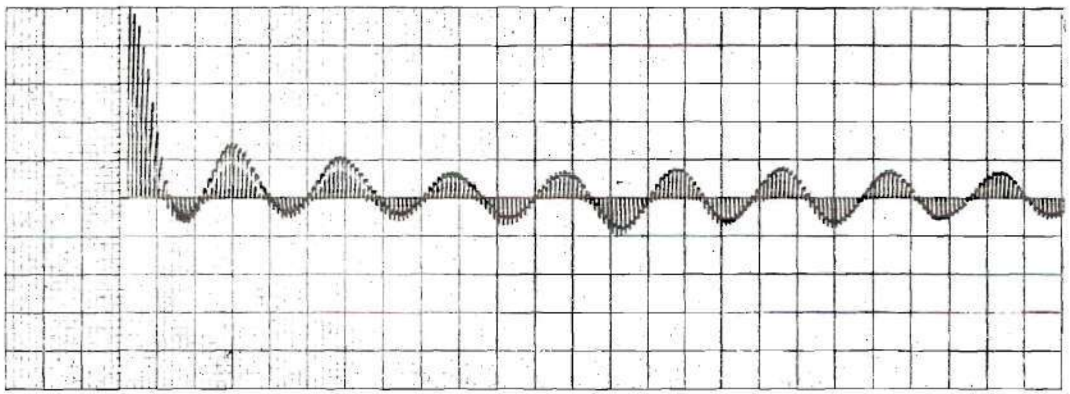


Figure 18. Autocorrelation Function of a Sine Wave 20 db Below Random Noise.

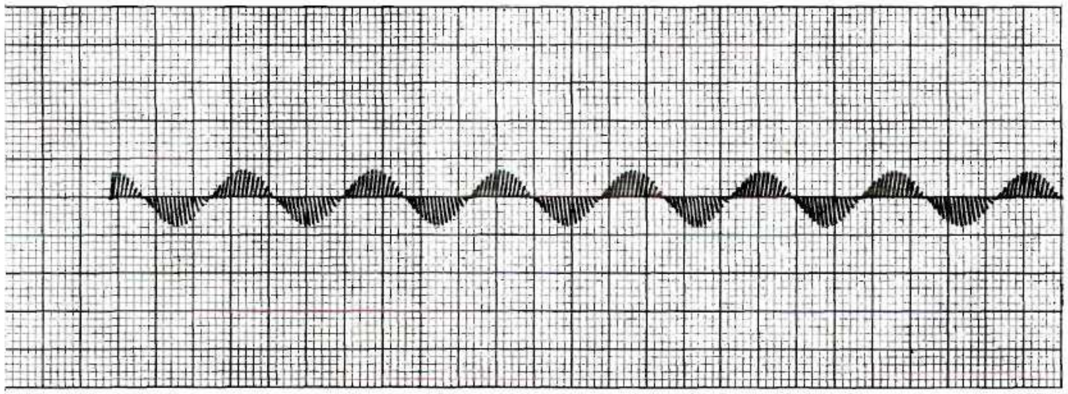


Figure 19. Crosscorrelation Function of a Sine Wave with a Sine Wave 40 db Below Random Noise.

periodic signals hidden in noise.

The various tests described above are indicative of the performance to be expected of the individual functional units of the correlator and of the machine as a whole. They cover the range of signal frequencies from zero to one thousand cycles per second and signal voltages from zero to one hundred volts. The results indicate that the precision of each individual functional unit is within 1 per cent of the range of that unit, and that the overall accuracy of the correlator is such that each point on a computed correlation curve may be expected to differ from its true value by not more than 5 per cent of the peak value of the correlation curve. This figure of course refers only to the accuracy of the machine, and does not include errors dependent on the choice of a finite integration time. Drifts in the characteristics of component parts that would cause errors beyond these limits appear to occur slowly enough to be corrected by the routine calibration procedure that precedes the computation of each correlation function.

A P P E N D I X

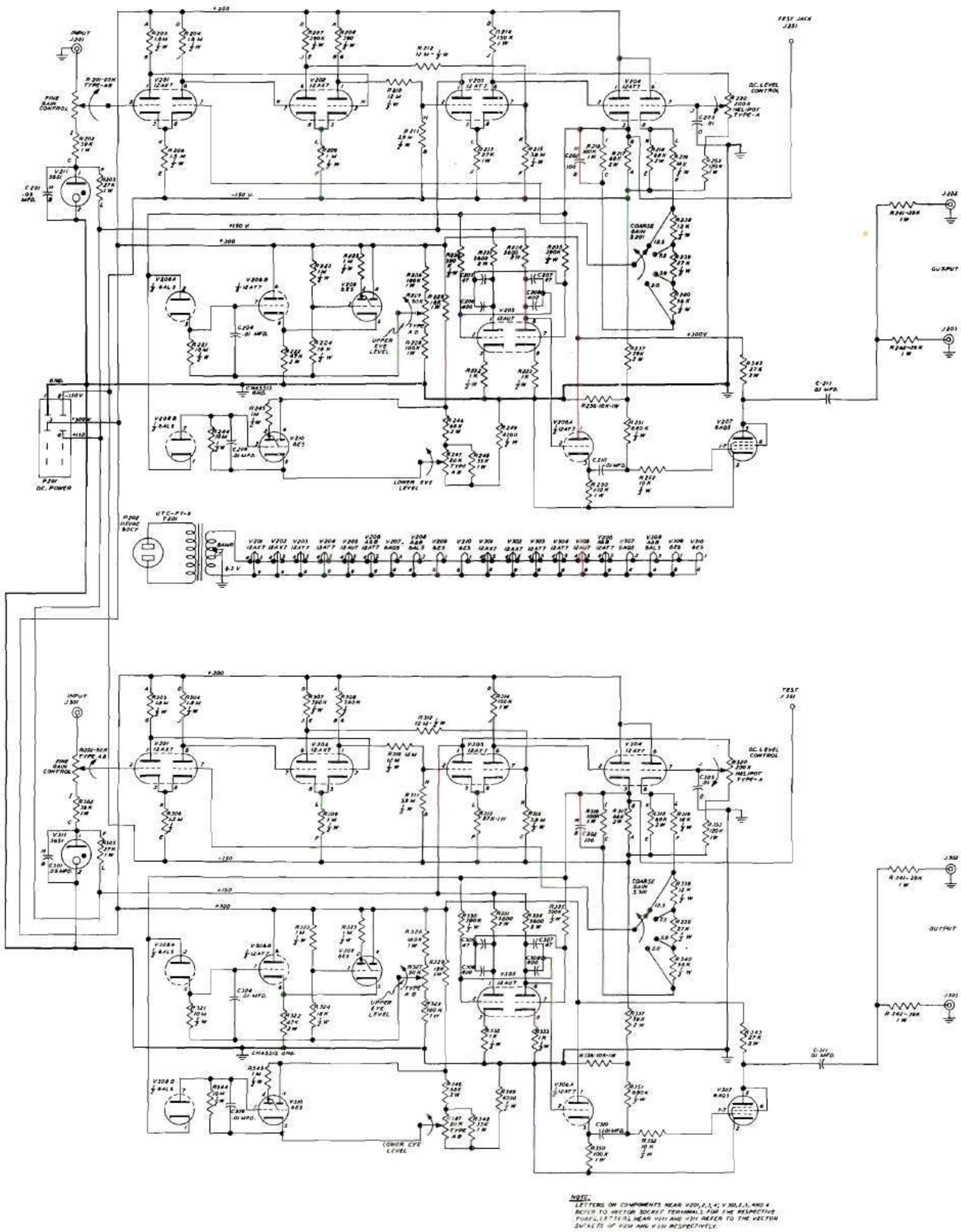


Figure 20. Modulator Unit Schematic Diagram.

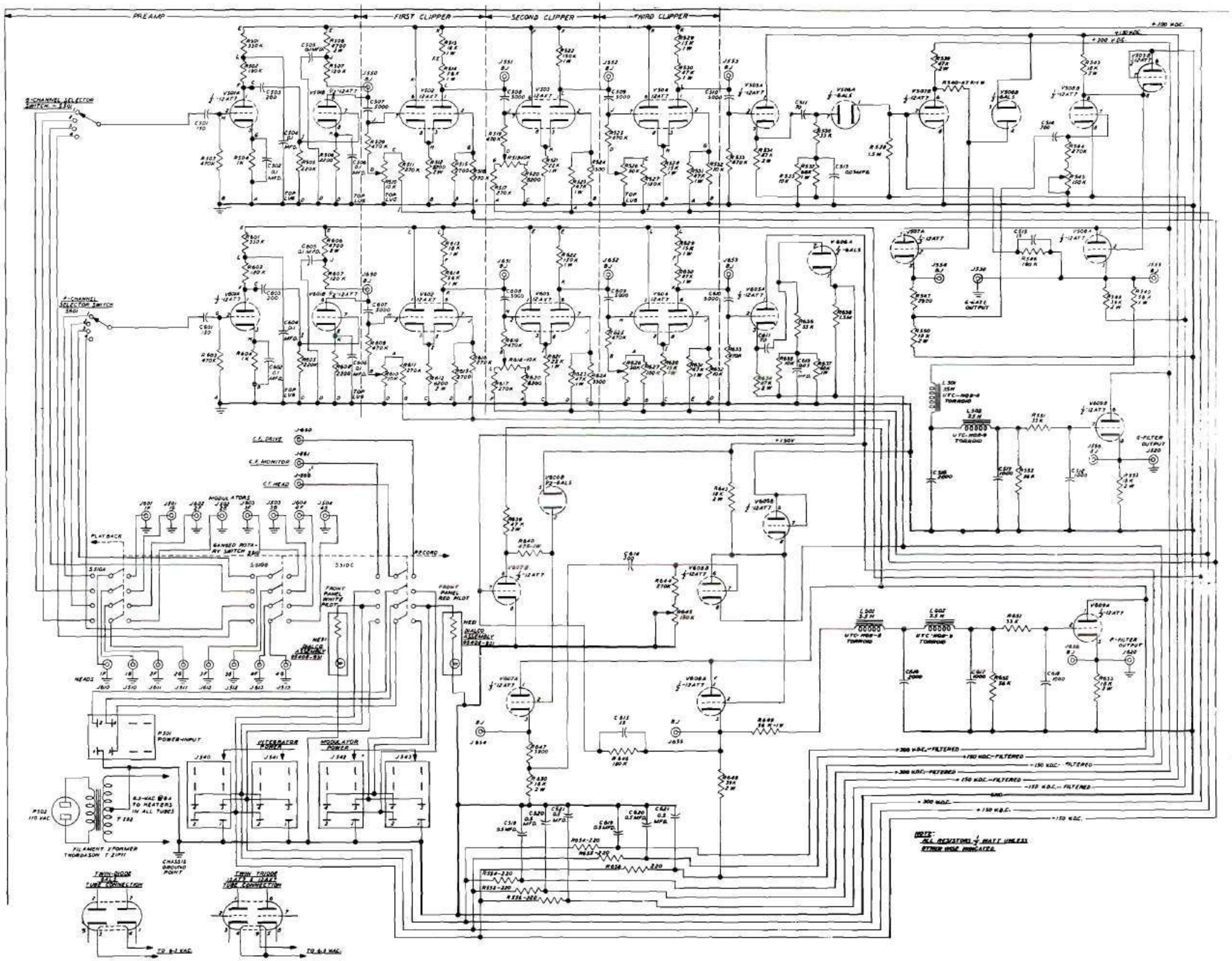


Figure 21. Demodulator Unit Schematic Diagram.

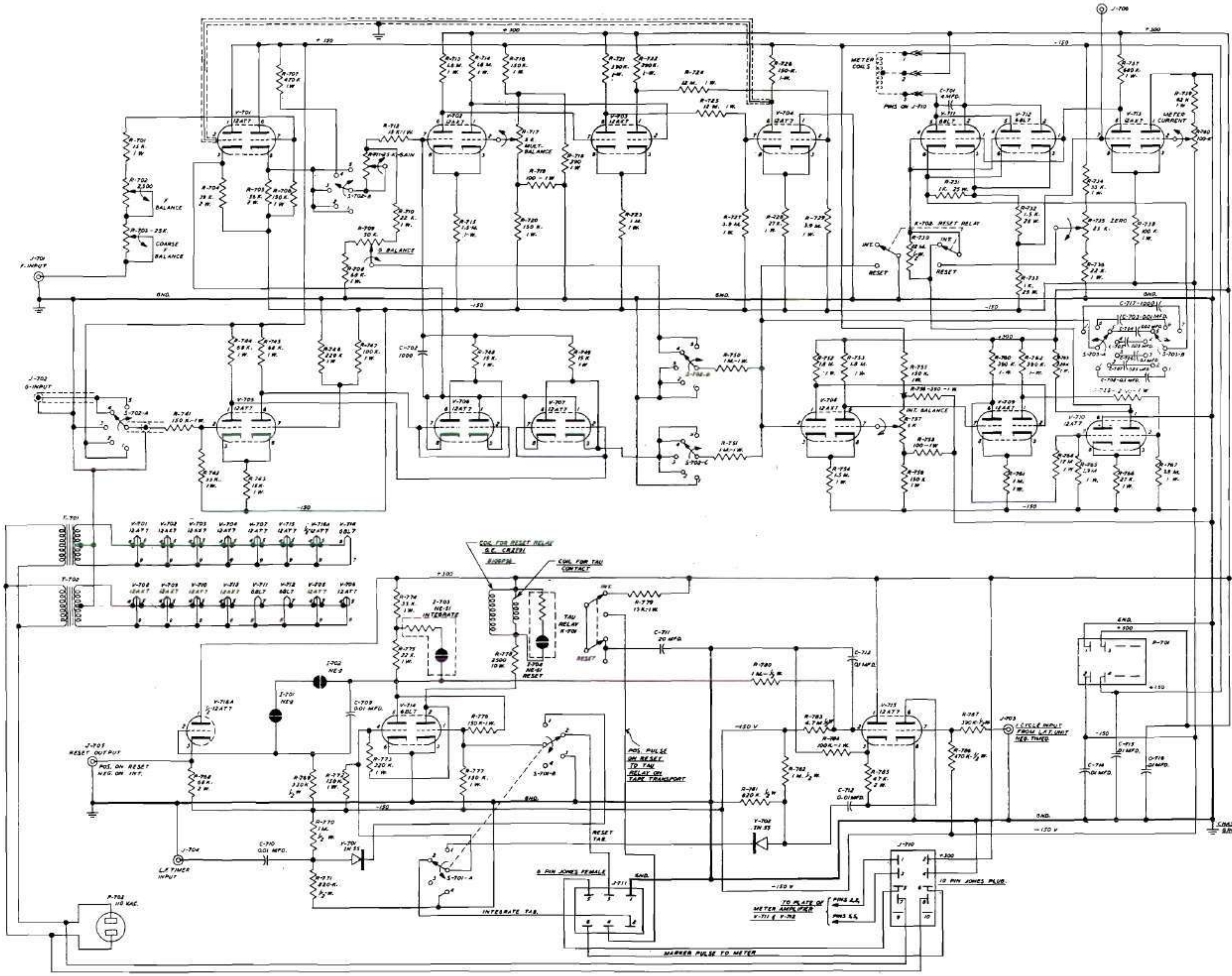


Figure 22. Multiplier - Integrator Schematic Diagram.

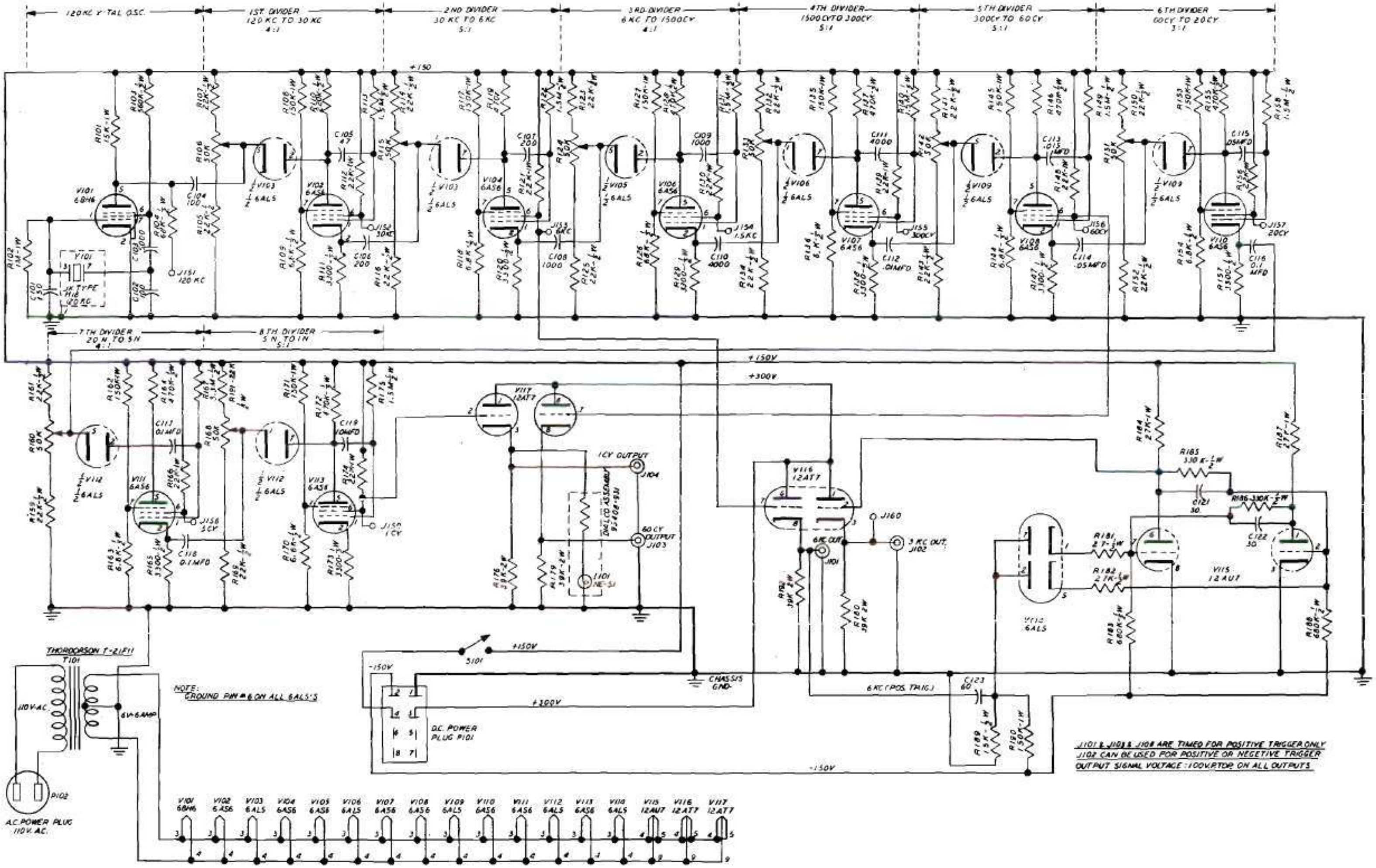


Figure 23. Timer Unit Schematic Diagram.

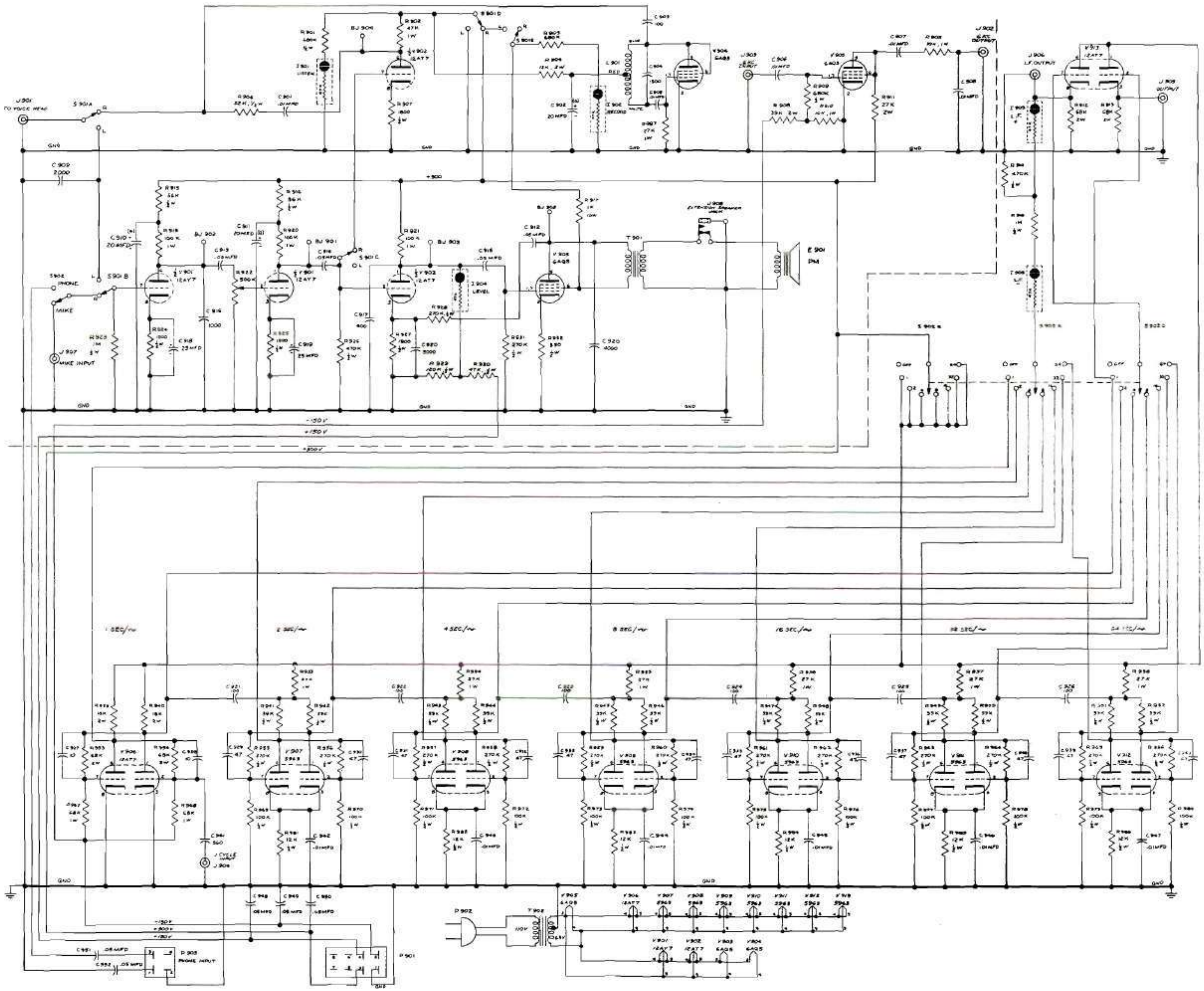


Figure 24. Voice Unit Schematic Diagram.

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